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ABSTRACT

Investments in Electricity Generating Capacity under Different Market Structures and with Endogenously Fixed Demand

by Anette Boom*

Investments in Generating Capacities between a monopolist and two competing firms are compared where the firms invest in their capacity and fix the retail price while electricity demand is uncertain. A unit price auction determines the wholesale electricity price when the firms compete. They know the level of demand when they bid their capacities. Total capacities can be larger or smaller with a duopoly than with a monopoly. If the two firms co-ordinate on a pareto dominant equilibrium, then the retail price is always higher and the social welfare lower in the competitive case, which exists only if capacity costs are not too high.

Keywords: Electricity Markets, Investments, Generating Capacities, Monopoly, Competition

JEL Classification: D42, D43, D44, L11, L12, L13

ZUSAMMENFASSUNG

Investitionen in Stromerzeugungskapazität bei verschiedenen Marktstrukturen und endogen fixierter Nachfrage

Die Investitionen in Stromerzeugungskapazität von einem Monopolisten werden mit denen zweier konkurrierender Unternehmen verglichen. Dabei investieren die Unternehmen in ihre Kapazität und setzen ihren Einzelhandelspreis, bevor sich die unsichere Nachfrage realisiert hat. Im Falle konkurrierender Firmen bestimmt sich der Großhandelspreis in einer nicht-diskriminierenden Auktion. Die Unternehmen kennen die Nachfragerealisation, wenn sie dort Ihre Gebote abgeben. Die Gesamtkapazität im Duopol kann sowohl größer als auch kleiner sein als im Monopol. Falls die zwei Unternehmen sich jedoch auf ein paretodominantes Gleichgewicht koordinieren, dann ist der Einzelhandelspreis immer höher und die soziale Wohlfahrt immer niedriger im Wettbewerbsgleichgewicht als im Monopol, wobei ersteres nur bei relativ geringen Kapazitätskosten existiert.

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1 Introduction

In many industrialised countries the market for electricity has been liberalised. Until the end of the eighties there was almost no competition among electricity suppliers. The market was characterised by regional monopolies that were either private enterprises, which had to comply with some kind of price regulation, or public utilities. The Electricity Pool of England and Wales and the so-called North Pool of the Scandinavian countries were the first attempts to organise a market for electricity and to introduce competition into the electricity industry. Other countries followed.

Whereas the introduction of competition was rather successful in these two regions, others, like California and New Zealand, experienced major crises with an explosion of wholesale prices and black-outs.[1] The focus of this paper is, however, not to figure out what went wrong when California and New Zealand opened their markets for competition,[2] but rather to investigate, whether the incentives to invest in generating capacity can be suboptimal under competition compared to a monopoly market.

Why should this be the case? The electricity market like many other markets is characterised by an uncertain demand. Electricity can, however, usually not be stored. All competing firms must use the same distribution network, and the inflows and outflows of electricity into this network have to be balanced at each point in time. If the balance cannot be preserved, then the network collapses and none of the firms can sell electricity anymore. This creates externalities that might be better internalised by a monopolist than by competing firms. The monopolist might install larger generating capacities, because he cannot free-ride on the capacity investments of others. In addition he can realise higher returns on his capacities in the rare cases of a high demand. He tends, however, to produce less than is socially efficient and would therefore need and build fewer generating capacities.

There are some indications that competing generators underinvest in their generating capacity as long as competition is not perfect. Von der Fehr and Harbord (1997) as well as Castro-Rodriguez *et al.* (2001) show that from a social welfare point of view firms would build suboptimal low levels of generating capacity, if the industry price coincides with their marginal cost of generating electricity, when the industry's capacities are sufficient to satisfy demand at this price, and with the market clearing price otherwise. By

[1]See e.g. *The Economist* from March 7, 1998, p. 46, and from February 10, 2001, and for the latest crisis in New Zealand *Modern Power Systems* from August 2001, p. 11.

[2]For analyses of the Californian electricity crisis see, e.g., Joskow (2001), Borenstein *et al.* (2001), Borenstein (2002) and Wilson (2002).

choosing suboptimal low levels of capacities firms can secure higher revenues in case of high demand realisations. The inefficiency disappears only if the number of firms approaches infinity.[3] They also prove that firms invest more in their generating capacity, if the spot market price exceeds marginal costs at a fixed margin. In addition von der Fehr and Harbord (1997) endogenise the spot market price of electricity for an inelastic demand that is ex ante uncertain in the capacity decision stage, and known, when the firms bid for the possibility to supply electricity in the auction. The auction is a unit price auction à la von der Fehr and Harbord (1993). They conclude that the firms underinvest in capacity as long as the distribution of the uncertain inelastic demand is concave, meaning skewed to the lower end of the distribution. But neither of the two compares the market outcome under competition with the one generated by a monopoly.

Contrary to von der Fehr and Harbord (1997), we consider consumers with an elastic demand for electricity. They can, however, not instantaneously respond to price signals. In the first stage two firms invest in generating capacity. Then each firm offers the consumers a contract that guarantees them a certain retail price and the delivery of electricity as long as delivery is possible. The consumers accept the contract with the lowest price. Afterwards nature chooses the level of the demand shock. After observing demand, firms bid prices in the wholesale market in order to get the right to deliver the electricity they can generate with their capacity to the network. The wholesale market is modelled as a unit price auction à la von der Fehr and Harbord (1997) and (1993).[4] Although there is a controversial debate whether a discriminatory auction should be preferred to a uniform auction design, most of the existing electricity markets are still uniform auctions.[5] Since the two firms commit to retail prices before the auction takes place, demand is inelastic in the auction as in von der Fehr and Harbord (1997). It is, however, not exogenous as in their framework, but endogenously determined by a competition for consumers in the retail market.

The fact that consumers cannot instantaneously respond to price signals is due to the imperfect metering technology that is used by most customers.

[3]This confirms the result of Borenstein and Holland (2002) who prove efficiency for perfectly competitive wholesale markets for electricity with price responsive demand.

[4]An alternative approach in order to model unit price auctions has been suggested by Green and Newbery (1992). It is based on Klemperer and Meyer (1989). They assume that firms bid differentiable supply functions, whereas von der Fehr and Harbord (1997) and (1993) assume that they bid step functions.

[5]An exception is the British market where a discriminatory auction has been introduced with the New Electricity Trading Arrangements in 2001. For a comparison of a uniform versus a discriminatory versus a Vickrey auction design see Fabra *et al.* (2002)

This technology does not register how much electricity they consume at a given point in time, and cannot communicate current market prices. In a companion paper (Boom, 2002) I abstract from this problem and assume that consumers can instantaneously respond to market prices and can therefore directly participate in the spot market for electricity. Both papers were inspired by the proponents of a better metering technology who argue that such a technology would result in much more elastic demands, reduce peak demands and improve the performance of liberalised electricity markets (see Borenstein, 2002; Faruqui *et al.*, 2001). For perfectly competitive electricity markets with perfectly price responsive demand they can even show that firms install the socially efficient levels of generating capacities (Borenstein and Holland, 2002). Most of the existing electricity markets are, however, not characterised by perfect competition. Therefore we analyse here a market with an oligopolistic structure.

It turns out that without a sophisticated metering technology the monopolist might install a smaller or larger capacity (than the two competitors together) at not too high of a capacity cost. If we focus, however, on subgame perfect Nash equilibria that are not pareto dominated, then the two duopoly firms invest more than the monopolist. The social welfare is, nevertheless, always higher under a monopoly than in the competitive setting, because the monopoly price is always lower than the duopoly price. These results contrast with those of the companion paper, Boom (2002), where the monopoly nearly always invests less and where the social welfare is always improved by competition.

2 The Model

There are two generators of electricity $j = A, B$, and a mass of electricity consumers that is normalised to one. They suffer from demand shocks and have a quasilinear utility function. Let their surplus function be given by

$$V(x;\varepsilon,r) = U(x,\varepsilon) - rx = x - \varepsilon - \frac{(x-\varepsilon)^2}{2} - rx, \tag{1}$$

where x is the consumed electricity, r is the retail price paid per unit for electricity, and ε is the demand shock. It hits all the consumers alike and is uniformly distributed on the interval $[0, 1]$. The demand for electricity can be derived from maximising $V(x;\varepsilon,r)$ with respect to x and results in

$$x(r,\varepsilon) = \max\{1 + \varepsilon - r, 0\}. \tag{2}$$

Note that the single consumer's demand has no weight in the total demand. Thus, he cannot influence the balance of supply and demand on the grid and would therefore always accept the lowest retail price offered. If the offered retail prices are identical, he then chooses each of the two price offers with equal probability.

The variable costs of generating electricity is assumed to be constant and, for the sake of simplicity, equal to zero for both firms. Thus the costs of firm j consist only of the costs of capacity which are assumed to be:

$$C(k_j) = zk_j, \tag{3}$$

where z is a constant unit cost of capacity and k_j the generation capacity installed by firm j. Firms decide on their capacity k_j and on their retail price offer r_j before they know the level of demand. When they bid their capacity in the electricity wholesale market, the demand shock is already realised and the retail price is already determined. Therefore the market demand is known for sure and does not respond to changes in the wholesale price.

The wholesale market price of electricity is determined in a unit price auction of the type introduced by von der Fehr and Harbord (1997) and (1993). Such an auction was at the heart of the Electricity Pool in England and Wales before the reform in 2001, and still is in place in other liberalised markets like, e.g., the Nord Pool in Scandinavia or the Spanish wholesale market.[6]. Firms have to bid a price p_j at which they are willing to supply their whole generating capacity. For the sake of simplicity the firms cannot bid other quantities.[7] The auctioneer must secure the balance of supply and demand on the grid if possible.[8] Therefore he orders the bids according to their prices and determines the marginal bid that is just necessary to equal supply and demand. The price of the marginal bid is the spot market price that is payed to all the generators for each unit that is dispatched on the grid no matter whether they bid a lower price.[9] The capacity of the supplier that has bid a

[6]See Bergman *et al.* (1999).

[7]Thus, we do not consider the problem of strategic withholding of capacity in order to raise the auction price. See Crampes and Creti (2001) for such an analysis.

[8]Transmission constraints are not considered here, although they might interact with constraints in the generating capacity. See Wilson (2002) for insights into this problem and for the analysis of isolated transmission constraints Borenstein *et al.* (2000), Joskow and Tirole (2000) and Léautier (2001)

[9]This differs the analysis here from simple Bertrand competition as in Kreps and Scheinkman (1983) where the undercutting firm receives only its own price per unit sold even if its capacity is too low to serve all the customers and some of them have to pay the price of the competitor with the next highest price.

price below the marginal price is dispatched completely, whereas the marginal supplier is only allowed to deliver that amount of electricity necessary to balance supply and demand. If the supplied capacity at a certain bid price is insufficient to satisfy demand but would be more than sufficient to satisfy demand at the next highest bid price, then the auctioneer sets the price in between the two bid prices at that level that ensures the balance.[10]

Since in our framework demand does not respond to changes in the wholesale price and since the total amount of installed capacities can also not be influenced by the wholesale price, the auctioneer may also fail to find a price that balances supply and demand in the market. Then a black-out occurs. No firm can sell and deliver electricity, and all the firms realise zero profits. If total capacities are sufficient to satisfy demand, the auctioneer accepts only price offers that do not exceed the maximum price level $\bar{p}$ that ensures zero profits for the buyer in the auction.

The game proceeds as follows:

1. The two generating firms simultaneously choose their respective capacities k_A and k_B.

2. The firms simultaneously offer contracts to the consumers that specify a retail price r_A or r_B, respectively. The consumers sign the contract with the lowest price or, sign each contract with probability one half, if both prices are identical.

3. Nature determines the demand shock ε.

4. Both firms bid a price p_j for their whole capacity k_j in the wholesale market.

5. The auctioneer determines the market clearing price p, if this is possible, and which generator is allowed to deliver which amount of electricity to the grid.

6. If supply and demand cannot be balanced, a black-out occurs. The consumers are not served and do not pay anything to the generators. If the balance on the wholesale market can be achieved, the consumers are served and pay the contracted retail price for each unit of their demand to the firm with which they signed the contract. The firms have to pay the wholesale price for each unit of electricity that their

[10] According to Wilson (2002) we assume an integrated system because participation in the auction is compulsory if a generating firm wants to sell electricity.

contracted consumers required and receive the wholesale price for each unit of electricity that they were allowed to dispatch on the grid.

It is assumed that the two firms can co-ordinate on a pareto dominant Nash equilibrium if there are multiple Nash equilibria in one of the stages.

3 The Monopolist's Capacity Choice

As a benchmark case we analyse how much a monopolist would invest in generation capacity, if he had to choose his capacity and to fix his retail price r before the uncertainty of demand is resolved. Note that with a monopolist a wholesale market does not exist. The monopolist's profit function is given by:

$$\pi_m(r,k) = \begin{cases} \int_{\max\{r-1,0\}}^{1} r(1+\varepsilon-r)d\varepsilon - zk & \text{if } r \geq 2-k, \\ \int_{\max\{r-1,0\}}^{k-1+r} r(1+\varepsilon-r)d\varepsilon - zk & \text{if } \max\{0,1-k\} \\ & \leq r < 2-k, \\ -zk & \text{if } r < \max\{0,1-k\}. \end{cases} \tag{4}$$

By differentiating the monopolist's profit function (4) with respect to r the optimal retail price for a given generation capacity can be calculated and is characterised in lemma 1.

Lemma 1 *For a given generation capacity k, the monopolist's profit maximising retail price is $r^*(k)$ with*

$$r^*(k) = \max\left\{\frac{3}{4}, 2-k\right\}.$$

Proof: See appendix A. ■

The monopolist sets a price that coincides with the unrestricted monopoly price of the expected demand, as long as his generation capacity is large enough ($k \geq \frac{5}{4}$) to satisfy even the largest possible demand at this price. For lower generation capacities ($0 \leq k < \frac{5}{4}$) the retail price decreases in the generation capacity. The monopolist sets a price that ensures no electricity outages for all possible demand shocks ε. Therefore black-outs would never occur under the scenario considered here.

Substituting the optimal price from Lemma 1 into the monopolist's profit function (4), differentiating with respect to k, and setting it equal to zero yields the monopolist's capacity choice, which is given in proposition 1.

Proposition 1 *The monopolist chooses the generation capacity*

$$k_m^* = \begin{cases} \frac{5}{4} - \frac{z}{2} & \textit{if } z \leq \frac{1}{2}, \\ \\ 0 & \textit{if } z > \frac{1}{2}. \end{cases}$$

The retail price in equilibrium is

$$r_m^* = \frac{3}{4} + \frac{z}{2},$$

as long as the investment in generation capacity is positive, i.e. $z \leq \frac{1}{2}$.

Proof: See appendix A. ■

The monopolist's investment decreases in the capacity cost z, but is discontinuous at $z = \frac{1}{2}$ because even optimal capacity levels and an optimal retail price would result in negative profits. The retail price increases in the capacity cost z.

4 Investments in Generation Capacity with Two Competing Firms

4.1 The Wholesale Market

If two firms compete, a wholesale market exists. Both firms commit in an earlier stage to a retail price. In addition the demand shock ε can already be observed by all market participants, therefore total market demand is fixed and known to be:

$$d(r_A, r_B, \varepsilon) = x\left(\min\{r_A, r_B\}, \varepsilon\right).$$

The contracted demand of firm j is given by:

$$d_j(r_j, r_h, \varepsilon) = \begin{cases} x(r_j, \varepsilon) & \text{if } r_j < r_h, \\ \frac{1}{2}x(r_j, \varepsilon) & \text{if } r_j = r_h, \\ 0 & \text{if } r_j > r_h, \end{cases} \quad \text{with } j, h \in \{A, B\}, j \neq h. \tag{5}$$

In principle we can distinguish two different situations. First, total capacity might be smaller than the market demand ($d(r_j, r_h, \varepsilon) > k_j + k_h$), in which case the auctioneer would not find any auction price that balances demand and supply and there would be a black-out; firms' profits would be $f_j(p_j, p_h, r_j, r_h, \varepsilon) = 0$. Note that the investments in generation capacity are sunk at this stage. Second, if total capacity is sufficient to serve the market demand ($d(r_j, r_h, \varepsilon) \leq k_j + k_h$), then the auction price is:

$$p(p_j, p_h, \varepsilon) = \left\{ \begin{array}{ll} p_j & \text{if } d(r_j, r_h, \varepsilon) > k_h, \\ p_h & \text{if } d(r_j, r_h, \varepsilon) \leq k_h, \end{array} \right\} \text{ and } p_j \geq p_h, \tag{6}$$

and the auctioneer dispatches the generating capacities of the two firms according to their price bids. The quantity of electricity that firm j is allowed to transmit to the network is given by:

$$y_j(p_j, p_h, \varepsilon) = \begin{cases} \min\{k_j, d(r_j, r_h, \varepsilon)\} & \text{if } p_j < p_h, \\ & \\ \frac{1}{2}\min\{k_j, d(r_j, r_h, \varepsilon)\} & \\ +\frac{1}{2}\max\{d(r_j, r_h, \varepsilon) - k_h, 0\} & \text{if } p_j = p_h, \\ & \\ \max\{d(r_j, r_h, \varepsilon) - k_h, 0\} & \text{if } p_j > p_h. \end{cases} \tag{7}$$

Thus, firm j's profit in terms of its own bid price p_j and its rival's bid price p_h is

$$f_j(p_j, p_h, r_j, r_h, \varepsilon) = r_j d_j(r_j, r_h, \varepsilon)) + p(p_j, p_h, \varepsilon)(y_j(p_j, p_h, \varepsilon) - d_j(r_j, r_h, \varepsilon)).$$

Note that $y_j(p_j, p_h, \varepsilon) + y_h(p_j, p_h, \varepsilon) = d_j(r_j, r_h, \varepsilon) + d_h(r_j, r_h, \varepsilon) = d(r_j, r_h, \varepsilon)$ must hold. The analysis of the firms' best responses in bid prices is presented in detail in appendix B and results in the following lemma.

Lemma 2 *If both firms have installed enough generation capacity to satisfy their own contracted demand ($k_j \geq d_j(r_j, r_h)$ for $j = A, B$) then the bid prices and the auction price satisfy $p_A = p_B = p(p_A, p_B, \varepsilon) = 0$ and each firm's profit net of capacity costs in equilibrium is $f_j(r_j, r_h, \varepsilon) = r_j d_j(r_j, r_h, \varepsilon))$ for $j = A, B$. If the total capacities installed are sufficient to satisfy the market demand ($k_A + k_B \geq d(r_j, r_h, \varepsilon)$), but if one firm j, cannot serve its own contracted demand ($k_j < d_j(r_j, r_h)$), then the bid prices satisfy $p_h = \bar{p}(r_j, r_h, \varepsilon) = p(p_j, p_h, \varepsilon)$ and $p_j \leq \hat{p}(r_j, r_h, \varepsilon) < \bar{p}(r_j, r_h, \varepsilon)$ with*

$$\bar{p}(r_j, r_h, \varepsilon) = \frac{r_j d_j(r_j, r_h, \varepsilon)}{d_j(r_j, r_h, \varepsilon) - k_j} \text{ and}$$

$$\hat{p}(r_j, r_h, \varepsilon) = \frac{r_j d_j(r_j, r_h, \varepsilon)}{\min\{k_h, d(r_j, r_h, \varepsilon)\} - d_h(r_j, r_h, \varepsilon)}.$$

Profits are $f_j(r_j, r_h, \varepsilon) = 0$ *and* $f_h(r_j, r_h, \varepsilon) = r_j d_j(r_j, r_h, \varepsilon) + r_h d_h(r_j, r_h, \varepsilon)$.

Proof: See appendix B. ■

Given that both firms can serve their contracted demand, each firm prefers to undercut its rival during the auction, because no firm wants to become a net payer. Thus, the Nash equilibrium is a zero auction price and each firm's profit is limited to the revenues earned from its contracted demand. Now consider a situation where one firm cannot serve its own contracted demand, and the other cannot only serve its own contracted demand, but can also make up for its rival's deficit. The deficit firm cannot avoid becoming a net payer during the auction. It can, however, minimize its net demand position by undercutting. The firm with the generation surplus is always a net supplier of electricity here. The unique Nash equilibrium in this situation is characterised by the surplus firm always bidding the maximum price. The deficit firm undercuts sufficiently, so that the surplus firm has no incentive to undercut itself. The deficit firm cannot realise a positive profit anymore, whereas the surplus firm can appropriate all the market's rents.

4.2 The Retail Price Competition

In principle the firms can use three strategies in the retail price competition: They can undercut their rival and contract the whole, yet uncertain, demand (see equation (5)). They can offer the same retail price as their rival, thus contracting half of the market demand, or they can request a higher price without contracting any demand. Undercutting yields the following expected profit:

$$\underline{\pi}_j(r_j, r_h) = \begin{cases} \int_{\max\{0, r_j - 1\}}^{\min\{1, k_j + r_j - 1\}} r_j x(r_j, \varepsilon) d\varepsilon & \text{if } \max\{1 - k_j, 0\} \leq r_j < r_h, \\ \\ 0 & \text{if } 0 \leq r_j < \min\{1 - k_j, r_h\}. \end{cases} \tag{8}$$

Firm j can only realise positive profits if the demand shock is, on the one hand small enough that it can serve its own contracted demand, and, on the other hand, large enough that the market demand is positive.

If firm j sets the same retail price as its rival, then its expected profit depends on the relative capacities of the two firms. If the considered firm j has a smaller capacity than its rival, the structure of its expected profit is the same as in the undercutting case, except that the firm realises only half of the market demand:

$$\pi_j(r_j, r_h)\left.\right|_{r_j=r_h} = \begin{cases} \int_{\max\{0, r_h-1\}}^{\min\{1, 2k_j+r_h-1\}} \frac{r_h x(r_h,\varepsilon)}{2} d\varepsilon & \text{if } r_h \geq \max\{1-2k_j, 0\}, \\ 0 & \text{if } 0 \leq r_h < 1-2k_j \end{cases} \tag{9}$$

for $k_j \leq k_h$. If firm j has, however, a larger capacity than firm h, it can appropriate all the rents in the market, if firm h is not able to serve its contracted demand and if firm j's surplus of capacity above its contracted demand makes up for firm h's deficit. For $k_j > k_h$ the expected profit is

$$\pi_j(r_j, r_h)\left.\right|_{r_j=r_h} = \begin{cases} \int_{\max\{0, r_h-1\}}^{1} \frac{r_h x(r_h,\varepsilon)}{2} d\varepsilon & \text{if } r_h \geq 2-2k_h, \\ \int_{\max\{0, r_h-1\}}^{2k_h+r_h-1} \frac{r_h x(r_h,\varepsilon)}{2} d\varepsilon + \int_{2k_h+r_h-1}^{\min\{k_h+k_j+r_h-1, 1\}} r_h x(r_h,\varepsilon) d\varepsilon & \text{if } \max\{1-2k_h, 0\} < r_h < 2-2k_h, \\ \int_{0}^{\min\{k_h+k_j+r_h-1, 1\}} r_h x(r_h,\varepsilon) d\varepsilon & \text{if } \max\{1-k_j-k_h, 0\} < r_h < 1-2k_h, \\ 0 & \text{if } 0 \leq r_h < 1-k_j-k_h. \end{cases} \tag{10}$$

If firm j sets a higher retail price than its rival, it has no contracted demand. It can, however, earn positive revenues when its rival cannot serve its contracted demand at its price r_h and firm j's capacity is large enough to step in. Then firm j can appropriate the whole rent via the auction. Thus, the expected profit is:

$$\bar{\pi}_j(r_j, r_h) = \begin{cases} 0 & \text{if } r_j > r_h \geq 2 - k_h, \\ \int_{\max\{0, r_h - 1 + k_h\}}^{\min\{1, r_h - 1 + k_h + k_j\}} r_h x(r_h, \varepsilon) d\varepsilon & \text{if } \max\{1 - k_h - k_j, 0\} \\ & \quad \leq r_h < \min\{r_j, \\ & \quad 2 - k_h\}, \\ 0 & \text{if } 0 \leq r_h < \min\{rj, \\ & \quad 1 - k_h - k_j\}. \end{cases} \quad (11)$$

From the analysis of the firms' profit functions one can derive each firm's best response in retail prices. This is done in appendix C in detail. If the sum of both firms generation capacities is rather large, both firms will always want to undercut each other as in the usual Bertrand competition without any capacity constraints and strategic considerations concerning the wholesale market. The resulting Nash equilibrium is $r_h = r_j = 0$ and yields zero profits for both firms.

If the aggregate generation capacity in the market is smaller, one can distinguish the symmetric case with $k_A = k_B$ and the asymmetric case with $k_A \neq k_B$. Let us first consider the asymmetric, but not too asymmetric case with $k_j > k_h$ and $k_h \geq \frac{k_j - 1}{2}$. Then the best response of firm j with the larger capacity would be characterised by undercutting as long as $r_h > \hat{r}$. It is characterised by $r_j > r_h$ for $\max\{0, 1 - 2k_h\} < r_h \leq \hat{r}$, by $r_j \geq r_h$ for $\max\{0, 1 - k_h - k_j\} \leq r_h \leq max\{0, 1 - 2k_h\}$, and by indifference for $0 \leq r_h < 1 - k_h - k_j$, because firm j's profit is then zero no matter which retail price it chooses. Firm h with the smaller capacity undercuts if $r_j > r'_j$, and chooses the same price as the larger provider j if $r''_j \leq r_j \leq r'_j$. It sets $r_h > r_j$ if $\max\{0, 1 - k_j - k_h\} \leq r_j < r''_j$ and is indifferent because of zero profits for $r_j = 0$ or $0 \leq r_j < 1 - k_j - k_h$. The critical retail prices $\hat{r}$, r'_j and r''_j depend on the two firms' capacity levels and are defined in appendix C. One can show, however, that $r''_j < \hat{r} < r'_j$ always holds. The Nash equilibrium is again $r_h = r_j = 0$ for $k_h + k_j \geq 1$ and $r_h < 1 - k_h - k_j$ as well as $r_j < 1 - k_h - k_j$ for $k_h + k_j < 1$. In both cases the firms realise zero profits.

Now consider the very asymmetric case with $k_h < \frac{k_j - 1}{2}$. Firm j can still serve the whole market for any possible demand shock ε at prices where firm h cannot even serve half of the market when they split the market at $r_h = r_j$. Again firm h undercuts if $r_j > r'_j$, it sets $r_h = r_j$, if $1 - 2k_h \leq r_j \leq r'_j$, and it is indifferent between undercutting, setting $r_h = r_j$ and $r_h > r_j$, if $2 - k_j \leq r_j < 1 - 2k_h$, because firm h would realise zero profits anyway.

For $0 < r_j < 2 - k_j$ firm h sets $r_h > r_j$ and can earn positive profits again, because firm j is no longer able to serve any demand possible. For $r_j = 0$ firm h is indifferent between all $r_h \geq 0$, because profits are again zero. Firm j's best response does not change in principle. The Nash equilibrium with $r_h = r_j = 0$ still exists, but there are other Nash equilibria where firm h realises zero and firm j positive profits. In these equilibria firm j sets $r_j \in [2 - k_j, 1 - 2k_h]$, where firm h realises zero profits no matter which price it sets, and firm h undercuts or sets $r_h > r_j$ if $r_j = \max\{3/4, 2 - k_j\}$. The results for asymmetric generation capacities of the two firms are summarised in the following lemma:

Lemma 3 *If the two firms differ in their generation capacity ($k_A \neq k_B$), then there are no Nash equilibria in retail prices where both firms realise positive profits. The Nash equilibrium in retail prices with $r_A^* = r_B^* = 0$ always exists. For $k_A + k_B < 1$ there are also multiple Nash equilibria with $r_A^* < 1 - k_A - k_B$ and $r_B^* < 1 - k_A - k_B$. All these equilibria result in zero profits for both firms.*

For $k_h < \frac{k_j - 1}{2}$ with $j, h = A, B$ and $j \neq h$ there are, in addition, multiple Nash equilibria with $\max\{r_h^*, 2 - k_j\} \leq r_j^* \leq \min\{1 - 2k_h, 3/4\}$. If $k_h < \min\left\{1/8, \frac{k_j - 1}{2}\right\}$ holds, then there is an additional equilibrium with either $r_j^* = 3/4 < r_h^*$ for $k_j > 5/4$ or $r_j^* = 2 - k_j \leq r_h^*$ for $1 < k_j \leq 5/4$. The low capacity firm h realises zero profits in all these additional Nash equilibria and firm j with the larger capacity:

$$\pi_j(r_j^*, r_h^*) = \min\{r_j^*, r_h^*\} \left(\frac{3}{2} - \min\{r_j^*, r_h^*\} \right) > 0.$$

For $k_A \neq k_B$ there are no other Nash equilibria in retail prices.

Proof: See appendix C . ■

If the two firms are symmetric in their generation capacities ($k_A = k_B$) and the capacities are not too large, both firms undercut, as long as the rivals price exceeds $\hat{r}$. When the rival sets its price at $\hat{r}$, each firm is indifferent between setting a higher price and the same price as the rival. If the rival's price is below $\hat{r}$, but not smaller than $1 - k_A - k_B$, then both firms want to set a higher price than their rival. If the rival sets a retail price of zero or a price below $1 - k_A - k_B$, then the considered firm is indifferent between undercutting, setting a higher or the same price, because all three options result in zero profits. Thus, the same Nash equilibrium or equilibria exist(s) as in the asymmetric case with zero equilibrium profits. In addition there is a Nash equilibrium with $r_A = r_B = \hat{r} > \max\{0, 1 - k_A - k_B\}$, where both firms realise positive profits in equilibrium. Our results concerning the competition in retail prices with symmetric generation capacities are summarised in lemma 4.

Lemma 4 *If the two firms have the same generation capacity $k_A = k_B = k$ then there is always a Nash equilibrium in retail prices with $r_A = r_B = 0$. For $k < 1/2$ there are also multiple Nash equilibria with $r_A < 1 - 2k$ and $r_B < 1 - 2k$. All these equilibria result in zero profits for both firms. For $k < \sqrt{5/2}$, there is an additional Nash equilibrium with*

$$r_A^* = r_B^* = \begin{cases} 2 - \sqrt{2}k & \text{if } 0 \leq k < \frac{1}{\sqrt{2}}, \\ \\ \frac{1}{2}\left(3 - \sqrt{4k^2 - 1}\right) & \text{if } \frac{1}{\sqrt{2}} \leq k < \sqrt{\frac{5}{2}}, \end{cases}$$

where the expected equilibrium profits are

$$\pi_A\left(r_A^*, r_B^*\right) = \pi_B\left(r_A^*, r_B^*\right) = \begin{cases} k^2\left(1 - \frac{k}{\sqrt{2}}\right) & \text{if } 0 \leq k < \frac{1}{\sqrt{2}}, \\ \frac{1}{8}\left(1 - 4k^2 + \right. \\ \qquad \left. 3\sqrt{4k^2 - 1}\right) & \text{if } \frac{1}{\sqrt{2}} \leq k < \sqrt{\frac{5}{2}}. \end{cases}$$

Proof: See appendix C . ■

In the following section we assume that the two firms are able to co-ordinate for given capacities on the equilibrium that pareto dominates all the other possible Nash equilibria in retail prices. If both firms choose symmetric capacities with $k_A = k_B = k < \sqrt{5/2}$, the pareto dominant Nash equilibrium results in the retail prices $r_A^* = r_B^* > 0$ given in Lemma 4. With asymmetric capacities and $k_h < \min\left\{\frac{k_j - 1}{2}, \frac{1}{8}\right\}$ the pareto dominant Nash equilibrium is characterised by $r_j^* = \max\{3/4, 2 - k_j\} < r_h^*$. If the two firms' capacities satisfy $\frac{1}{8} \leq k_h < \frac{k_j - 1}{2}$, then the retail prices $r_h^* = r_j^* = 1 - 2k_h$ are set in the pareto dominant Nash equilibrium.

4.3 The Firms' Investments in Generation Capacity

The firms anticipate the resulting retail prices and the prices on the wholesale market when they decide on their generation capacities. For a very low capacity of its rival, a firm can either choose a very large capacity and ensure itself monopoly revenues, or at least restricted monopoly revenues, or it can choose the same small generation capacity as its rival in order to generate positive revenues. Firm j's profit is:

$$\Pi_j(k_j, k_h) = \begin{cases} -zk_j & \text{if } k_j < k_h, \\ k_j^2\left(1 - \frac{k_j}{\sqrt{2}}\right) - zk_j & \text{if } k_j = k_h, \\ -zk_j & \text{if } k_h < k_j \leq 2k_h + 1, \\ (2 - k_j)\left(k_j - \frac{1}{2}\right) - zk_j & \text{if } 2k_h + 1 < k_j \leq \frac{5}{4}, \\ \frac{9}{16} - zk_j & \text{if } k_j > \frac{5}{4}, \end{cases} \tag{12}$$

for $0 \leq k_h < \frac{1}{8}$. If the rival's capacity is larger, but still small, the firm can no longer earn monopoly revenues, but for some small levels of k_h, still positive revenues, if it invests in a very much larger capacity than its rival. Its profit is:

$$\Pi_j(k_j, k_h) = \begin{cases} -zk_j & \text{if } k_j < k_h, \\ k_j^2\left(1 - \frac{k_j}{\sqrt{2}}\right) - zk_j & \text{if } k_j = k_h, \\ -zk_j & \text{if } k_h < k_j \leq 2k_h + 1, \\ \max\left\{(1 - 2k_h)\left(\frac{1}{2} + 2k_h\right), 0\right\} - zk_j & \text{if } 2k_h + 1 < k_j, \end{cases} \tag{13}$$

for $\frac{1}{8} \leq k_h < \frac{1}{\sqrt{2}}$. If the rival chooses intermediate levels of capacities, firm j's revenues from investing in the same level of capacity changes. Firm j's profit is:

$$\Pi_j(k_j, k_h) = \begin{cases} -zk_j & \text{if } k_j < k_h, \\ \frac{1}{8}\left(1 - 4k_j^2 + 3\sqrt{4k_j^2 - 1}\right) - zk_j & \text{if } k_j = k_h, \\ -zk_j & \text{if } k_h < k_j, \end{cases} \tag{14}$$

for $\frac{1}{\sqrt{2}} \leq k_h < \sqrt{\frac{5}{2}}$. If the firm's rival chooses very large capacities, then firm j can no longer earn positive revenues independent of its own capacity level.

Firm j's profit is:

$$\Pi_j(k_j, k_h) = -zk_j \tag{15}$$

for $k_h > \sqrt{\frac{5}{2}}$. From these profit functions one can derive each firm's best response function in generation capacity and the resulting subgame perfect Nash equilibria. This is done in detail in appendix D. Since both firms are symmetric, the best response functions for the two firms are also symmetric and depend on the level of the capacity costs z. For very low levels of the rivals capacity k_h firm j can always monopolize the market by choosing the same capacity as the monopolist. This is always the best response as long as the capacity cost is low enough to ensure a positive monopoly profit. If the rival's capacity increases, then firm j can still monopolize the market, but must increase its own capacity beyond the optimal monopoly level. Thus, firm j's profit from monopolization decreases when the rival' capacity increases. Therefore it is optimal for firm j to reduce its capacity dramatically at a certain threshold of the rival's capacity k_h and to switch either to a symmetric capacity choice, where both firms share the market, or to zero capacity when monopolization as well as sharing yields zero profits. Depending on the level of the capacity costs z, firm j's best response to higher levels of the rival's capacity k_h is either to install no capacity or to choose the same capacity and to share the market. For very large capacities of the rival it is always optimal for firm j to install no capacity. The best responses of the two firms and the resulting Nash equilibria are depicted in figure 1 for different levels of capacity costs .

From figure 1 it is obvious that there are multiple subgame perfect Nash equilibria in which the firms choose identical capacities and share the market at low levels of capacity costs. For intermediate levels of capacity costs there are still multiple Nash equilibria where the firms choose identical capacities. In addition there are, however, two equilibria where one of the two firms chooses the monopoly capacity and the other does not invest. This happens, if capacity costs are so high that the profits from sharing the market, when each firm chooses the monopoly level of capacity, is negative. For high levels of capacity costs the sharing equilibria vanish, because choosing the same capacity and sharing the market yields always negative profits. Only the two subgame perfect Nash equilibria, where one firm monopolizes the market, do still exist. They disappear when the capacity costs are so high that even a monopolist can not generate positive profits in expectation. Our results concerning the investments of the two competing firms in generation capacities are summarised in proposition 2, where we use

$$\underline{k} \equiv \frac{1}{\sqrt{2}}\left(1-\sqrt{1-2z\sqrt{2}}\right), \tag{16}$$

which defines the smallest capacity that ensures zero profit, when both firms choose the same capacity,

$$\bar{k} \equiv \left\{ k \in \left[\frac{1}{\sqrt{2}}, \sqrt{\frac{5}{2}}\right] \middle| \frac{1-4k^2+3\sqrt{4k^2-1}}{8} - zk = 0 \right\}, \tag{17}$$

which defines the largest capacity that ensures zero profit, when both firms choose the same capacity, and

$$\begin{aligned}\tilde{k} \quad \equiv \quad & \left\{ k \in \left[0, \frac{1}{2}\right] \middle| k^2\left(1-\frac{k}{\sqrt{2}}\right) - zk = \right. \\ & \left. (1-2k)\left(\frac{1}{2}+2k\right) - z(2k+1) \right\},\end{aligned} \tag{18}$$

which defines the capacity where the necessary capacity to monopolize is as profitable as choosing an identical capacity as one's rival.

Proposition 2 *In the subgame perfect Nash equilibria the two competing firms choose identical generation capacities with*

$$k_A^* = k_B^* = k_d^* \in [\tilde{k}, \bar{k}], \ \textit{if the capacity costs satisfy } 0 \le z < 0.2118.$$

They choose either identical generation capacities with

$$k_A^* = k_B^* = k_d^* \in [\min\{\tilde{k}, \underline{k}\}, \bar{k}] \ \textit{or assymmetric capacities with}$$

$$k_j^* = k_m^* \ \textit{and} \ k_h^* = 0, \quad j, h = A, B, \quad j \neq h, \ \textit{if } 0.2118 \le z < \frac{1}{2\sqrt{2}},$$

where k_m^* is defined in proposition 1. The firms choose only asymmetric capacities with

$$k_j^* = k_m^* \ \textit{and} \ k_h^* = 0, \quad j, h = A, B, \quad j \neq h \ \textit{if} \ \frac{1}{2\sqrt{2}} \le z < \frac{1}{2}.$$

For $z \ge \frac{1}{2}$ both firms do not invest in generation capacity in equilibrium. The retail price in the equilibria with identical positive capacities is

$$r_d^* = \begin{cases} 2-\sqrt{2}k_d^* & \textit{if } \min\{\tilde{k}, \underline{k}\} \le k_d^* < \frac{1}{\sqrt{2}}, \\ \frac{1}{2}\left(3-\sqrt{4(k_d^*)^2-1}\right) & \textit{if } \frac{1}{\sqrt{2}} \le k_d^* < \bar{k}. \end{cases}$$

Whereas the retail price coincides with the monopoly price r_m^*, given in proposition 1, if the firms choose asymmetric capacities in equilibrium such that one firm monopolizes the market.

Proof: See Appendix D. ■

Note that regardless of whether the firms play a competitive equilibrium with $k_A = k_B \in [\min\{\tilde{k}, \underline{k}\}, \bar{k}]$ or a monopoly equilibrium, no black-outs occur independent of the demand shock ε.

In the following we focus mainly on subgame perfect equilibria, which are not dominated by other equilibria. By comparing each firm's profits in the different equilibria described in proposition 2 one can conclude:

Corollary 1 *If the capacity cost satisfies $0 \leq z < 0.2118$, then there is a unique pareto dominant subgame perfect Nash equilibrium where both firms choose $\hat{k}$, which is defined in (19). For $0.2118 \leq z < \frac{1}{2\sqrt{2}}$ the subgame perfect equilibria that are not pareto dominated are either characterised by both firms choosing $\hat{k}$ or by one firm choosing k_m^* and the other installing zero capacities. If $\frac{1}{2\sqrt{2}} \leq z < \frac{1}{2}$ holds, then there are two equilibria, which are not pareto dominated, with one firm choosing k_m^* and the other installing zero capacities. For $z \geq \frac{1}{2}$ there exists only one equilibrium where both firms do not invest in capacities.*

The capacity $\hat{k}$ is the capacity that maximises each firm's profit, if both firms choose the same level of capacity:

$$\hat{k} = \text{argmax}_{k \in [\frac{1}{\sqrt{2}}, \bar{k}]} \left\{ \frac{1 - 4k^2 + 3\sqrt{4k^2 - 1}}{8} - zk \right\}. \tag{19}$$

For intermediate levels of capacity costs the equilibrium with $k_A = k_B = \hat{k}$ pareto dominates all the other competitive equilibria with $k_A = k_B \in [\min\{\tilde{k}, \underline{k}\}, \bar{k}]$, but not the two monopoly equilibria with $k_A = k_m^*$ and $k_B = 0$ and $k_B = k_m^*$ and $k_A = 0$, because the monopolist in the monopoly equilibrium realises always higher profits than each single firm in the competitive equilibrium. In addition the monopoly equilibria do, as well, not pareto dominate the competitive equilibrium with $k_A = k_B = \hat{k}$, because the firm without any generation capacity has zero profits, whereas it realises positive profits in the competitive equilibrium with $k_A = k_B = \hat{k}$. Thus, even if we consider only pareto dominant subgame perfect Nash equilibria, uniqueness cannot be achieved.

5 Comparison of the Monopoly with the Duopoly

In Figure 2 the total capacities in the monopoly and duopoly cases are delineated. The limits of the total capacities in the competitive equilibria, as well as the total capacity in the pareto dominant competitive equilibrium and the total capacity in the monopolistic equilibrium in the duopoly case are painted in blue. The capacity installed in the monopoly case is characterised by a red line. It is obvious that together the duopolists might invest more or less than the monopolist. If we assume, however, that the two firms can co-ordinate on a subgame perfect equilibrium, which is not pareto dominated then we arrive at proposition 3.

Proposition 3 *If the two firms in the duopoly case can always co-ordinate on a subgame perfect equilibrium, which is not pareto dominated by an other one, then the total capacity in the duopoly case exceeds the installed capacity of a monopolist for capacity costs that satisfy* $0 \leq z < 0.2118$*. It is the same or larger for* $0.2118 \leq z < \frac{1}{2\sqrt{2}}$*, and it is the same for* $z \geq \frac{1}{2\sqrt{2}}$.

Proof: The statement follows from $2\hat{k} > k_m^*$ for all $0 \leq z < \frac{1}{2\sqrt{2}}$. ■

Proposition 3 seems to confirm common wisdom that oligopolistic firms want to produce more and would, therefore, also install more capacity. If we compare, however, the prices in equilibrium for those subgame perfect Nash equilibria that are not pareto dominated, proposition 4 can then be derived.

Proposition 4 *If the two firms in the duopoly case can always co-ordinate on a subgame perfect equilibrium that is not pareto dominated by an other equilibrium, then the retail price in the duopoly case exceeds the retail price of the monopolist for capacity costs that satisfy* $0 \leq z < 0.2118$*. The retail price is the same or higher for* $0.2118 \leq z < \frac{1}{2\sqrt{2}}$*, and it is the same for* $z \geq \frac{1}{2\sqrt{2}}$.

Proof: The statement follows from substituting $\hat{k}$ into r_d^* from proposition 2 and comparing it with r_m^* from proposition 1. ■

Proposition 4 contradicts the common view that oligopolistic firms want to produce more and would therefore install larger capacities. Since the two firms would always set a higher retail price in the competitive equilibrium than a monopolist, consumers would always consume less than in the monopolistic case. Thus, the higher level of installed capacities in the competitive equilibrium are mainly a consequence of strategic considerations. Larger capacities and a higher retail price ensure that a firm has a higher chance to serve its own contracted demand. With a small capacity and low retail prices a firm risks losing all its profits in those cases where it can no longer meet its contracted demand.

As long as capacities are positive in the market equilibrium, consumers can always realise their desired consumption level, because black-outs do neither occur in the duopoly, nor in the monopoly case for any possible demand shock. Thus, social welfare for both cases is given by:

$$W = \int_0^1 U\left(x(r,\varepsilon),\varepsilon\right) d\varepsilon - zk, \tag{20}$$

where $U\left(x(r,\varepsilon),\varepsilon\right)$ is defined in equation (1). The delivery of electricity is certain in both cases. The higher prices that result in lower consumption levels and the larger capacities, which only increase the capacity costs without creating any extra gain from a more certain delivery in the competitive case, do explain proposition 5.

Proposition 5 *If the two firms in the duopoly case can always co-ordinate on a subgame perfect equilibrium that is not pareto dominated by any other equilibrium, then the social welfare in the duopoly case is smaller than in the case with a monopolist for capacity costs that satisfy* $0 \leq z < 0.2118$. *Social welfare is the same or smaller for* $0.2118 \leq z < \frac{1}{2\sqrt{2}}$, *and it is the same for* $z \geq \frac{1}{2\sqrt{2}}$.

Proof: The statement follows from substituting the relevant consumption levels $x(r,\varepsilon)$ into the social welfare function (20) and from comparing the social welfare achieved in a monopoly with the one in a competitive equilibrium. ■

If we take into account all possible competitive equilibria in the duopoly case, retail prices can also be lower than in the monopoly case. It turns out, however, that social welfare is nearly always lower in the duopoly case than in the monopoly. The reason is that in those equilibria where the retail prices are lower, the duopoly capacities are so much higher that capacity costs outweigh the gains of the consumers from higher consumption levels.

6 Conclusions

Given the multiplicity of subgame perfect Nash equilibria in the competitive case, it is not easy to derive clear cut conclusions from the analysis here. If we focus on subgame perfect Nash equilibria which are not pareto dominated by other equilibria, then it is not a problem that competitive firms do not invest enough in generating capacity. Their investments together usually exceed the capacity installed by a monopolist. Their retail price is, however, too high which leads to a lower social welfare than realised in the monopoly case.

Thus, in the case analysed here where consumers cannot respond directly to electricity prices, but are guaranteed a certain retail price before an uncertain demand is realised, competition is bad for social welfare. This contrasts with the results in a companion paper (Boom, 2002), where consumers can directly respond to electricity price changes and can therefore take part in the electricity auction. There competition is always beneficial for social welfare.

What drives our results here is the retail price competition where prices turn out to be relatively high for the installed capacities. A large installed capacity, as well as a high retail price saves a firm from the bad situation in which it is not able to satisfy the consumers' demand with whom it signed a contract. In this situation it would lose all its rents in the wholesale auction. Therefore it would be interesting to consider the same type of model if in case of an unsatisfied demand the loss would be less drastic. This can be expected if there would be more than one competitor. Another natural extension of the model considered here is to analyse the effect of a smaller maximum price in the auction which would punish the competitor, who is not able to meet his contracted demand, less. The analysis of a model with more competitors and smaller maximum prices are left to further research.

Appendix

A The Monopolist's Price and Capacity Choice

After integration the monopolist's profit function (4) is

$$\pi_m(r,k) = \begin{cases} \frac{r}{2}(2-r)^2 - zk & \text{if } r > 1, \\ r\left(\frac{3}{2} - r\right) - zk & \text{if } 2-k \le r \le 1, \\ \frac{r}{2}\left(2r - r^2 + k^2 - 1\right) - zk & \text{if } 0 \le r < 2-k, \end{cases}$$

for $k \geq 1$ and

$$\pi_m(r,k) = \begin{cases} \frac{r}{2}(2-r)^2 - zk & \text{if } r \geq 2-k, \\ \\ r\frac{k^2}{2} - zk & 1 \leq r < 2-k, \\ \\ \frac{r}{2}\left(2r - r^2 + k^2 - 1\right) - zk & \text{if } 1-k \leq r < 1, \\ \\ -zk & \text{if } 0 \leq r < 1-k, \end{cases}$$

for $0 \leq k < 1$. Differentiating $\pi_m(r,k)$ with respect to r yields that $\pi_m(r,k)$ has a maximum at $r^*(k) = \frac{3}{4}$, as long as $k \geq \frac{5}{4}$, and at $r^*(k) = 2-k$ for $0 \leq k < \frac{5}{4}$. Substituting these retail prices into $\pi_m(r,k)$ yields:

$$\Pi_m(k) = \begin{cases} \frac{9}{16} - zk & \text{if } k \geq \frac{5}{4}, \\ \\ \frac{5k}{2} - k^2 - 1 - zk & \text{if } 1 \leq k < \frac{5}{4}, \\ \\ \frac{1}{2}k^2(2-k) - zk & \text{if } 0 \leq k < 1. \end{cases}$$

Differentiating $\Pi_m(k)$ with respect to k yields that $\Pi_m(k)$ has a maximum at $k^*(z) = \frac{5}{4} - \frac{z}{2}$ for $0 \leq z \leq \frac{1}{2}$ and at $k^*(z) = \frac{1}{6}\left(4 + \sqrt{16 - 24z}\right)$ for $z > \frac{1}{2}$. The maximised profit, $\Pi_m(k^*(z))$, is continuous and monotonously decreasing in z. It becomes negative at $z = \frac{1}{2}$.

B The Nash Equilibrium in Price Bids on the Wholesale Market.

Here it is assumed that total capacities are sufficient to satisfy the market demand ($k_A + k_B \geq d(r_A, r_B, \varepsilon)$). Then, taking into account (7) each firm's profit function is given by:

$$f_j(p_j,p_h,r_j,r_h,\varepsilon) = \begin{cases} r_j d_j(r_j,r_h,\varepsilon) + p(p_j,p_h,\varepsilon) \\ \quad \cdot (\min\{k_j, d(r_j,rh,\varepsilon)\} - d_j(r_j,r_h,\varepsilon)) & \text{if } p_j < p_h, \\ \\ r_j d_j(r_j,r_h,\varepsilon) + \frac{p(p_j,p_h,\varepsilon)}{2} \\ \quad \cdot (\min\{k_j, d(r_j,rh,\varepsilon)\} - d_j(r_j,r_h,\varepsilon)) \\ \quad + \frac{p(p_j,p_h,\varepsilon)}{2} (d_h(r_j,r_h,\varepsilon) \\ \quad - \min\{k_h, d(r_j,rh,\varepsilon)\}) & \text{if } p_j = p_h, \\ \\ r_j d_j(r_j,r_h,\varepsilon) + p(p_j,p_h,\varepsilon) \\ \quad \cdot (d_h(r_j,r_h,\varepsilon) - \min\{k_h, d(r_j,rh,\varepsilon)\}) & \text{if } p_j > p_h. \end{cases}$$

If both firms are able to serve their own contracted demand, meaning $k_j \geq d_j(r_j,r_h,\varepsilon)$ with $j = A,B$, then both firms want to undercut their rival because by doing so they avoid being a net payer in the auction, but become a net receiver of payments. Therefore $p_j = p_h = 0 = p(p_j,p_h,\varepsilon)$ is the unique Nash equilibrium. Substituting this into $f_j(p_j,p_h,r_j,r_h,\varepsilon)$ yields $f_j(r_j,r_h,\varepsilon)$ from lemma 2 for $k_j \geq d_j(r_j,r_h,\varepsilon)$ with $j = A,B$.

Suppose now that only firm h can meet its own contracted demand ($k_h \geq d_h(r_j,r_h)$), whereas firm j cannot ($k_j < d_j(r_j,r_h)$). Then firm j is always a net payer and firm h a net receiver in the auction. Firm j minimizes its payments by always undercutting firm h. If firm h sets $p_h > p_j$, the auction price would be $p(p_j,p_h,\varepsilon) = p_h$ and its optimal price bid would be $p_h = \bar{p}(r_j,r_h,\varepsilon)$, given in lemma 2, which ensures zero profits for firm j and the profit $f_h(r_j,r_h,\varepsilon) = r_j d_j(r_j,r_h,\varepsilon) + r_h d_h(r_j,r_h,\varepsilon)$ for firm h. The optimal price bid from below would either be indeterminate, if both capacities were needed to satisfy market demand ($k_h < d(r_j,r_h,\varepsilon)$), or it would be $p_h = p_j - \mu$ with $\mu \to 0$ if $k_h \geq d(r_j,r_h,\varepsilon)$. The auction price would in both cases satisfy $p(p_j,p_h,\varepsilon) = p_j$ and firm h's profit would be $f_h(p_j,p_h,r_j,r_h,\varepsilon) = r_h d_h(r_j,r_h,\varepsilon) + p_j(\min\{k_h, d(r_j,rh,\varepsilon)\} - d_h(r_j,r_h,\varepsilon))$. Firm h prefers undercutting firm j's price as long as $p_j > \hat{p}(r_j,r_h,\varepsilon)$ holds, and $p_h = \bar{p}(r_j,r_h,\varepsilon)$ otherwise. Thus, there are multiple Nash equilibria with $p_j \leq \hat{p}(r_j,r_h,\varepsilon)$ and $p_h = \bar{p}(r_j,r_h,\varepsilon)$, and a unique auction price $p(p_j,p_h,\varepsilon) = \bar{p}(r_j,r_h,\varepsilon)$. Substituting the auction price into the two firms' profit functions yields $f_j(r_j,r_h,\varepsilon)$ and $f_h(r_j,r_h,\varepsilon)$ from lemma 2 for $k_j < d_j(r_j,r_h)$.

C The Nash Equilibrium in Retail Prices.

If firm j undercuts its rival's retail price, its best response is then

$$\underline{r}_j(r_h) = \begin{cases} \max\left\{2-k_j, \frac{3}{4}\right\} & \text{if } r_h > \max\left\{2-k_j, \frac{3}{4}\right\} \\ \\ r_h - \mu & \text{if } 0 \le r_h \le \max\left\{2-k_j, \frac{3}{4}\right\} \end{cases} \tag{21}$$

with $\mu \to 0$ being the smallest unit in which retail prices can be announced. If firm j sets $r_j > r_h$, then it is indifferent between all prices that satisfy this restriction, because its profit, given in (11), does not depend on the level of r_j. Therefore the overall best response is determined by the comparison of $\underline{\pi}_j(\underline{r}_j(r_h), r_h)$, derived from (8) and (21), with $\pi_j(r_j, r_h)\big|_{r_j=r_h}$ from (9) or (10), respectively, and with $\bar{\pi}_j(r_j, r_h)$ defined in (11).

Suppose that $k_j > k_h$. Then the overall best response of firm j for $k_j > k_h \ge \sqrt{5-k_j^2}$ is given by $r_j(r_h) = \underline{r}_j(r_h)$ from (21). For $\min\left\{k_j, \sqrt{5-k_j^2}\right\} > k_h \ge 0$ the overall best response is

$$r_j(r_h) \begin{cases} = \max\left\{2-k_j, \frac{3}{4}\right\} & \text{if } r_h > \max\left\{2-k_j, \frac{3}{4}\right\}, \\ \\ = r_h - \mu & \text{if } \hat{r} < r_h \le \max\left\{2-k_j, \frac{3}{4}\right\}, \\ \\ > r_h & \text{if } \max\{0, 1-2k_h\} < r_h \le \min\{\hat{r}, \\ & \quad \max\left\{2-k_j, \frac{3}{4}\right\}\}, \\ \\ \ge r_h & \text{if } \max\{0, 1-k_j-k_h\} < r_h \le \\ & \quad \min\left\{1-2k_h, \max\left\{2-k_j, \frac{3}{4}\right\}\right\}, \\ \\ \ge 0 & \text{if } 0 \le r_h \le \max\{0, 1-k_j-k_h\}. \end{cases} \tag{22}$$

with

$$\hat{r} = \begin{cases} \frac{3-\sqrt{2(k_h^2+k_j^2)-1}}{2} & \text{if } k_j \ge k_h > \min\{\sqrt{1-k_j^2}, k_j-1\}, \\ \\ 1-k_h & \text{if } 0 \le k_h \le k_j - 1, \\ \\ 2-\sqrt{k_h^2+k_j^2} & \text{if } 0 \le k_h \le \min\{\sqrt{1-k_j^2}, k_j\}. \end{cases} \tag{23}$$

Firm h's best response in retail prices is $r_h(r_j) = \underline{r}_j(r_h)$ for $k_j > k_h \geq \sqrt{\frac{5}{2}}$. For $\min\{k_j, \sqrt{\frac{5}{2}}\} > k_h \geq \max\left\{0, \frac{k_j-1}{2}\right\}$ firm h's best response in retail prices is given by

$$r_h(r_j) \begin{cases} = \max\left\{2 - k_h, \frac{3}{4}\right\} & \text{if } r_j > \max\left\{2 - k_h, \frac{3}{4}\right\}, \\ = r_j - \mu & \text{if } \max\left\{2 - k_h, \frac{3}{4}\right\} \geq r_j > r_j', \\ = r_j & \text{if } r_j' \geq r_j > r_j'', \\ > r_j & \text{if } r_j'' \geq r_j > \max\{0, 1 - k_j - k_h\}, \\ \geq 0 & \text{if } \max\{0, 1 - k_j - k_h\} \geq r_j \geq 0, \end{cases} \tag{24}$$

where the critical price r_j' for the rival with the larger capacity is defined as:

$$r_j' = \max\left\{\frac{3 - \sqrt{4k_h^2 - 1}}{2}, 2 - \sqrt{2}k_h\right\}, \tag{25}$$

and the critical price r_j'' as:

$$r_j'' = \max\left\{\frac{3 - \sqrt{4k_j^2 - 1}}{2}, \frac{5 - \sqrt{12k_h^2 + 6k_j^2 - 2}}{3}, 0\right\} \tag{26}$$

for $k_j > 1$ and

$$r_j'' = \begin{cases} \max\left\{\frac{3 - \sqrt{4k_j^2 - 1}}{2}, \frac{5 - \sqrt{12k_h^2 + 6k_j^2 - 2}}{3}\right\} & \text{if } k_j \geq k_h \geq \sqrt{\frac{1 - k_j^2}{2}}, \\ 2 - \sqrt{2k_h^2 + k_j^2} & \text{if } \sqrt{\frac{1 - k_j^2}{2}} > k_h \geq 0 \end{cases} \tag{27}$$

for $\frac{1}{\sqrt{2}} < k_j \leq 1$ and

$$r_j'' = \max\left\{2 - \sqrt{2}k_j, 2 - \sqrt{2k_h^2 + k_j^2}\right\} \tag{28}$$

for $0 \leq k_j < \frac{1}{\sqrt{2}}$. It can be shown that $r_j' > \hat{r} > r_j''$ holds for $k_j > k_h \geq \frac{k_j - 1}{2}$. Thus, $r_h = r_j = 0$ is the only Nash equilibrium in retail prices for

$k_j > \max\{1-k_h, k_h\}$ and $k_h \geq \frac{k_j-1}{2}$. There are multiple Nash equilibria with $r_j < 1-k_j-k_h$ and $r_h < 1-k_j-k_h$ for $1-k_h \geq k_j > k_h \geq \frac{k_j-1}{2}$.

For $\frac{k_j-1}{2} > k_h > 0$ firm h's best response in retail prices is

$$r_h(r_j) \begin{cases} = 2-k_h & \text{if } r_j > 2-k_h, \\ = r_j - \mu & \text{if } 2-k_h \geq r_j > r_j', \\ = r_j & \text{if } r_j' \geq r_j \geq 1-2k_h, \\ \geq 0 & \text{if } 1-2k_h > r_j \geq 2-k_j, \\ > r_j & \text{if } 2-k_j > r_j > 0, \\ \geq 0 & \text{if } r_j = 0, \end{cases} \tag{29}$$

where r_j' is defined in (25). Thus, $r_j \in [2-k_j, \min\{1-2k_h, 3/4\}]$ and $r_h \leq r_j$ is always an equilibrium. For $k_h < \min\left\{\frac{k_j-1}{2}, \frac{1}{8}\right\}$ an additional equilibrium exists with $r_j = \max\{2-k_j, 3/4\} < r_h$.

Now suppose that $k_A = k_B = k$, then each firm has the same best response in retail prices. If $k > \sqrt{\frac{5}{2}}$, then both firms' best response is given by $\underline{r}_j(r_h)$ from equation (21) and the only possible Nash equilibrium is $r_A = r_B = 0$. If $0 \leq k < \sqrt{\frac{5}{2}}$, then each firm's best response in retail prices is given by:

$$r_j(r_h) = \begin{cases} = \max\left\{2-k, \frac{3}{4}\right\} & \text{if } r_h > \max\left\{2-k, \frac{3}{4}\right\}, \\ = r_h - \mu & \text{if } \max\left\{2-k, \frac{3}{4}\right\} \geq r_h > \hat{r} \\ \geq r_h & \text{if } r_h = \hat{r} \\ > r_h & \text{if } \hat{r} > r_h > \max\{0, 1-2k\}, \\ \geq r_h & \text{if } \max\{0, 1-2k\} \geq r_h \geq 0, \end{cases} \tag{30}$$

with $\hat{r}$ from (23) with $k_j = k_h = k$. Then again there is always a Nash equilibrium with $r_A = r_B = 0$. If $k < 1/2$, then there are also multiple Nash equilibria with $r_A < 1-2k$ and $r_B < 1-2k$, which result as well in zero profits for both firms. In addition there is always a Nash equilibrium with $r_A = r_B = \hat{r}$ and positive profits for both firms.

D The Nash Equilibrium in Generation Capacities

From the maximization of $\Pi_j(k_j, k_h)$ given in (12), (13), (14) and (15) with respect to k_j one can derive the best response of firm j in its generation capacity k_j. It is given by:

$$k_j(k_h) = \begin{cases} \frac{5}{4} - \frac{z}{2} & \text{if } 0 \leq k_h < \frac{1}{8} - \frac{z}{4}, \\ 1 + 2k_h & \text{if } \frac{1}{8} - \frac{z}{4} \leq k_h < \tilde{k}, \\ k_h & \text{if } \tilde{k} \leq k_h < \bar{k}, \\ 0 & \text{if } k_h \geq \bar{k}, \end{cases} \tag{31}$$

for $0 \leq z < 0.2484$, where $\tilde{k}$ is defined in (18) and $\bar{k}$ in (17), by:

$$k_j(k_h) = \begin{cases} \frac{5}{4} - \frac{z}{2} & \text{if } 0 \leq k_h < \frac{1}{8} - \frac{z}{4}, \\ 1 + 2k_h & \text{if } \frac{1}{8} - \frac{z}{4} \leq k_h < \frac{1-2z+\sqrt{9+4z(z-5)}}{8}, \\ 0 & \text{if } \frac{1-2z+\sqrt{9+4z(z-5)}}{8} \leq k_h < \underline{k}, \\ k_h & \text{if } \underline{k} \leq k_h < \bar{k}, \\ 0 & \text{if } k_h \geq \bar{k}, \end{cases} \tag{32}$$

for $0.2484 \leq z < \frac{1}{2\sqrt{2}}$, where $\underline{k}$ is defined in (16), by

$$k_j(k_h) = \begin{cases} \frac{5}{4} - \frac{z}{2} & \text{if } 0 \leq k_h < \frac{1}{8} - \frac{z}{4}, \\ 1 + 2k_h & \text{if } \frac{1}{8} - \frac{z}{4} \leq k_h < \frac{1-2z+\sqrt{9+4z(z-5)}}{8}, \\ 0 & \text{if } k_h \geq \frac{1-2z+\sqrt{9+4z(z-5)}}{8}, \end{cases} \tag{33}$$

for $\frac{1}{2\sqrt{2}} \leq z < \frac{1}{2}$ and by

$$k_j(k_h) = 0 \tag{34}$$

for $z \geq \frac{1}{2}$. Checking for $k_j\left(k_h(k_j)\right) = k_j$ and $k_h\left(k_j(k_h)\right) = k_h$ yields the subgame perfect Nash equilibria described in Proposition 2.

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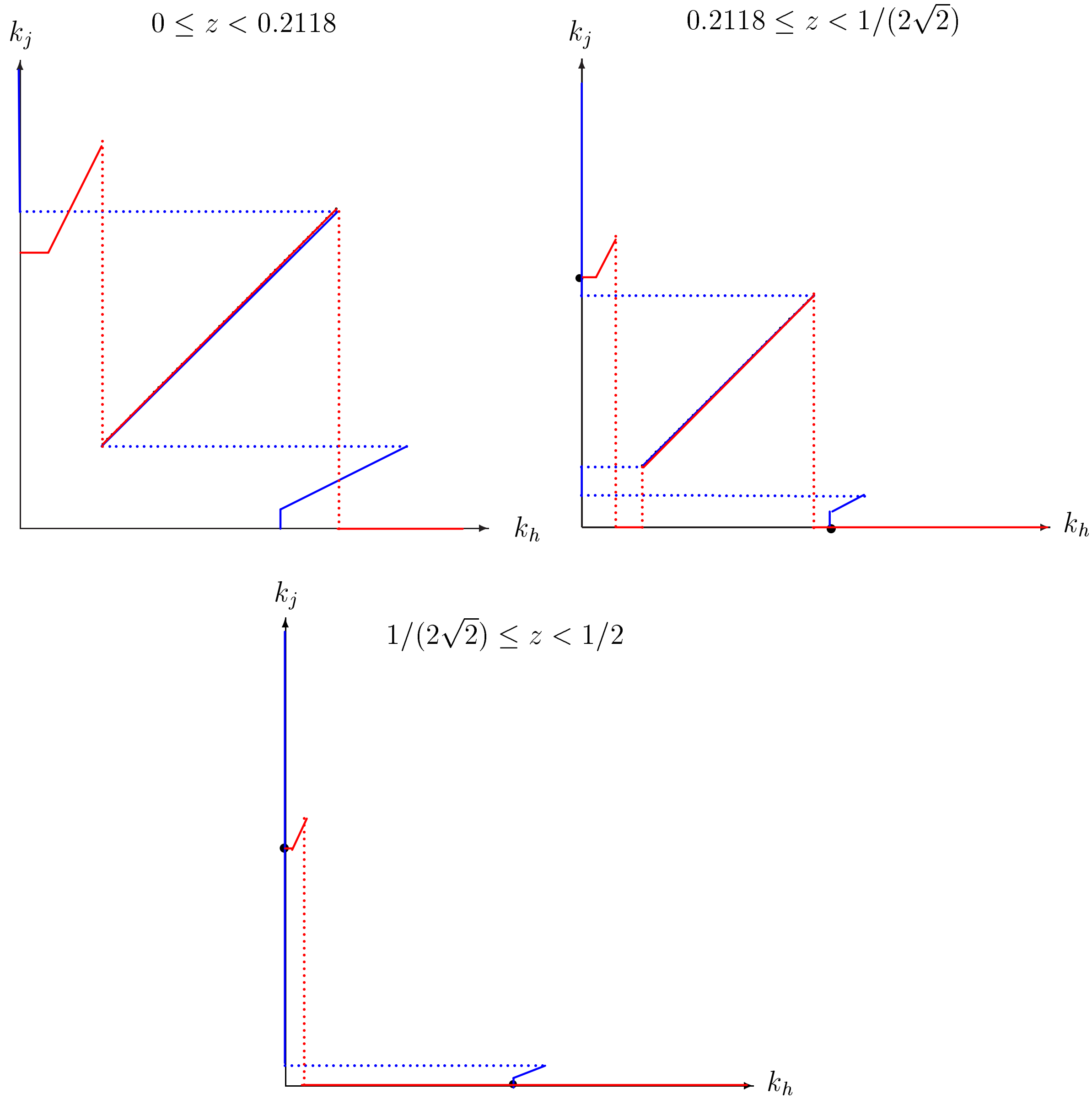

Figure 1: Nash Equilibria in Capacities

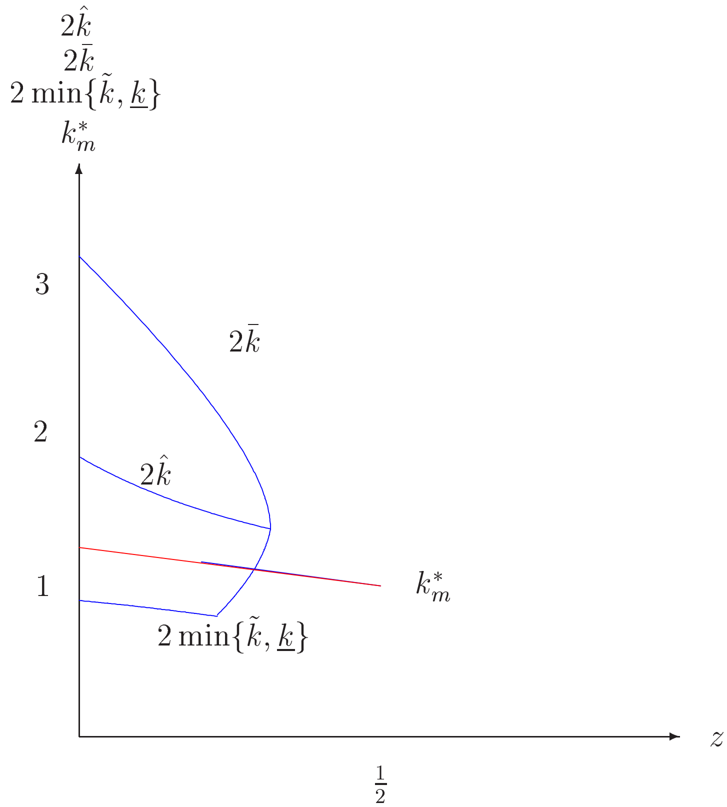

Figure 2: Total Capacities with a Duopoly and a Monopoly

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